

Precision Temperature Sensing with RTD Circuits

Author: *Bonnie C. Baker*
Microchip Technology Inc.

INTRODUCTION

One of the most widely measured phenomena in the process control environment is temperature. Common elements such as Resistance Temperature Detectors (RTDs), thermistors, thermocouples or diodes are used to sense absolute temperatures as well as changes in temperature. For an overview and comparison of these sensors, refer to Microchip's AN679, "Temperature Sensing Technologies".

Of these technologies, the platinum RTD temperature sensing element is the most accurate and stable over time and temperature. RTD element technologies are constantly improving, further enhancing the quality of the temperature measurement (see Figure 1). Typically, a data acquisition system conditions the analog signal from the RTD sensor, making the analog translation of the temperature usable in the digital domain.

This application note focuses on circuit solutions that use Platinum RTDs in the design. Initially, the RTD temperature sensing element will be compared to the negative temperature coefficient (NTC) thermistor, which is also a resistive temperature sensing element. In this forum the linearity of the RTD will be presented along with calibration formulas that can be used to improve the off the shelf linearity of the element. If more information is needed concerning the thermistor temperature sensor, refer to Microchip's AN685, "Thermistors in Single Supply Temperature Sensing Circuits". Finally, the signal conditioning path for the RTD system will be covered with complete application circuits from sensor or microprocessor.

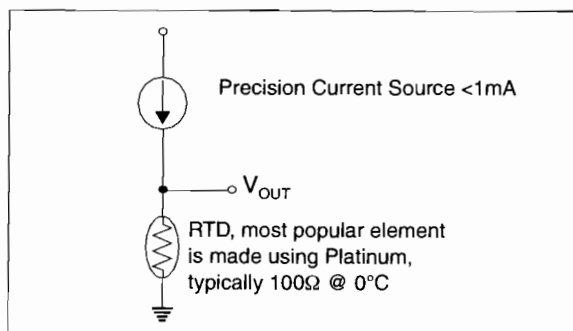


FIGURE 1: Unlike thermistors, RTD temperature sensing elements require current excitation.

RTD OVERVIEW

The acronym "RTD" is derived from the term "Resistance Temperature Detector". The most stable, linear and repeatable RTD is made of platinum metal. The temperature coefficient of the RTD element is positive. This is in contrast to the NTC thermistor that has a negative temperature coefficient as shown graphically in Figure 2. An approximation of the platinum RTD resistance change over temperature can be calculated by using the constant $0.00385\Omega/\Omega/^{\circ}\text{C}$. This constant is easily used to calculate the absolute resistance of the RTD at temperature.

$$RTD(T) = RTD_0 + T \times RTD_0 \times 0.00385\Omega/\Omega/^{\circ}\text{C}$$

where

$RTD(T)$ is the resistance value of the RTD element at temperature (Celsius),

RTD_0 is the specified resistance of the RTD element at 0°C , and

T is the temperature environment that the RTD is placed (Celsius).

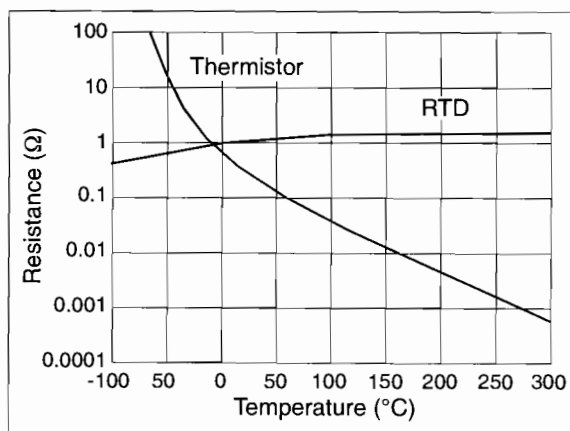


FIGURE 2: The temperature versus resistance characteristics of the RTD sensing element is considerably different than the thermistor sensor element. The RTD sensing element has a positive temperature coefficient and is considerably more linear.

The RTD element resistance is extremely low as compared to the resistance of an NTC thermistor element which ranges up to $1\text{M}\Omega$ at 25°C . Typical specified 0°C values for RTDs are 50, 100, 200, 500, 1000 or 2000Ω . Of these options, the 100Ω platinum RTD is the most stable over time and linear over temperature.

If the RTD element is excited with a current reference at a level that does not create a error due to self-heating, the accuracy can be $\pm 4.3^\circ\text{C}$ over its entire temperature range of -200°C to 800°C . If a higher accuracy temperature measurement is required, the linearity formula below (Calendar-Van Dusen Equation) can be used in a calculation in the processor engine or be used to generate a look-up table.

$$RTD(T) = RTD_0(1 + AT + BT^2(100CT^3 + CT^4))$$

where

$RTD(T)$ is the resistance of the RTD element at temperature,

RTD_0 is the specified resistance of the RTD element at 0°C ,

T is the temperature that is applied to the RTD element (Celsius), and

A , B , and C are constants derived from resistance measurements at 0°C , 100°C , and 260°C .

The linearity performance of a typical RTD is shown in Figure 3.

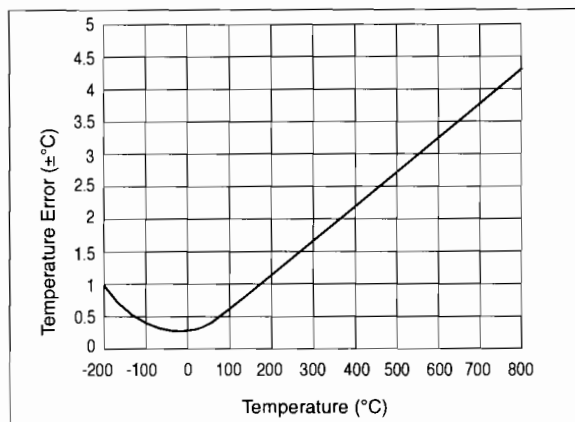


FIGURE 3: The linearity error of the Platinum RTD temperature sensor is small when compared to other sensors such as the thermocouple and thermistor.

The RTD element requires a current excitation. If the magnitude of the current source is too high the element will dissipate power and start to self-heat. Consequently, care should be taken to insure that $\leq 1\text{mA}$ of current is used to excite the RTD element.

The advantages and disadvantages of the RTD temperature sensing element is summarized in Table 1.

ADVANTAGES	DISADVANTAGES
Very Accurate and Stable	Expensive Solution
Fairly Linear to $\pm 4\%^\circ\text{C}$	Requires Current Excitation
Good Repeatability	Self-Heating
	Low Resistive Element

TABLE 1: RTD temperature sensing element advantages and disadvantages.

RTD CURRENT EXCITATION CIRCUIT

For best linearity, the RTD sensing element requires a stable current reference for excitation. This can be implemented in a number of ways, one which is shown in Figure 4. In this circuit, a voltage reference along with two operational amplifiers are used to generate a floating 1mA current source.

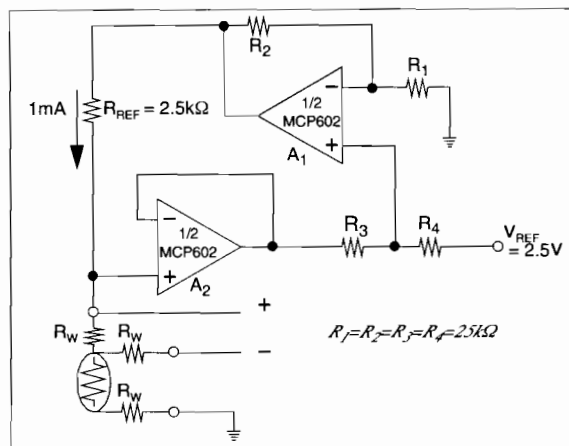


FIGURE 4: A current source for the RTD element can be constructed in a single supply environment from two operational amplifiers and a precision voltage reference.

This is accomplished by applying a 2.5V precision voltage reference to R_4 of the circuit. Since R_4 is equal to R_3 and the non-inverting input to A_1 is high impedance, the voltage drop across these two resistors is equal. The voltage between R_3 and R_4 is applied to the non-inverting input of A_1 . That voltage is gained by $(1 + R_2/R_1)$ to the output of the amplifier and the top of the reference resistor, R_{REF} . If $R_1 = R_2$, the voltage at the output of A_1 is equal to:

$$V_{OUTA1} = (1 + R_2/R_1) \times (V_{REF} - V_{R4})$$

$$V_{OUTA1} = 2 \times (V_{REF} - V_{R4})$$

where

V_{OUTA1} is the voltage at the output of A_1 and V_{R4} is the voltage drop across R_4 .

The voltage at the output of A_2 is equal to:

$$V_{OUTA2} = V_{REF} - V_{R4} - V_{R3}$$

This same voltage appears at the inverting input of A_2 and across to the non-inverting input of A_2 .

Solving these equations, the voltage drop across the reference resistor, R_{REF} is equal to:

$$V_{RREF} = V_{OUTA1} - V_{OUTA2}$$

$$V_{RREF} = 2 \times (V_{REF} - V_{R4}) - (V_{REF} - V_{R4} - V_{R3})$$

$$V_{RREF} = V_{REF}$$

where

V_{RREF} is the voltage across the reference resistor, R_{REF} and V_{R3} is the voltage drop across R_3 .

The current through R_{REF} is equal to:

$$I_{RTD} = V_{REF} / R_{REF}$$

This circuit generates a current source that is ratiometric to the voltage reference. The same voltage reference can be used in other portions of the circuit, such as the analog-to-digital (A/D) converter reference.

Absolute errors in the circuit will occur as a consequence of the absolute voltage of the reference, the initial offset voltages of the operational amplifiers, the output swing of A_1 , mismatches between the resistors, the absolute resistance value of R_{REF} and the RTD element. Errors due to temperature changes in the circuit will occur as a consequence of the temperature drift of the same elements listed above. The primary error sources over temperature are the voltage reference, offset drift of the operational amplifiers and the RTD element.

RTD SIGNAL CONDITIONING PATH

Changes in resistance of the RTD element over temperature is usually digitized through an A/D conversion as shown in Figure 5. The current excitation circuit shown in Figure 4 is used to excite the RTD element. With this style of excitation, the magnitude of the current source can be tuned to 1mA or less by adjusting R_{REF} . The voltage drop across the RTD element is sensed by A_3 then gained and filtered by A_4 . With this circuit, a three-wire RTD element is selected. This configuration minimizes errors due to wire resistance and wire resistance drift over temperature.

In this circuit, the RTD element equals 100Ω at 0°C . If the RTD is used to sense temperature over its entire range of -200 to 600°C , the range of resistance produced by the RTD would be nominally 23Ω to 331Ω . Since the

resistance range is relatively low, wire resistance and wire resistance change over temperature can skew the measurement of the RTD element. Consequently, a three wire RTD device is used to reduce these errors.

The errors contributed by the wire resistances, R_{W1} and R_{W3} , is subtracted from the circuit with the A_3 the operational amplifier circuit. In this configuration, R_1 and R_2 are equal and relatively high. The value of R_3 is selected to insure that the leakage currents through the resistor does not introduce errors to the current to the RTD element. The transfer function of this portion of the circuit is:

$$V_{OUTA3} = (V_{IN} - V_{W1})(1 + R_2/R_1) - V_{IN}(R_2/R_1)$$

where

$$V_{IN} = V_{W1} + V_{RTD} + V_{W3}$$

V_{W1} is the voltage drop across the wires to and from the RTD and

V_{OUTA3} is the voltage at the output of A_3

If it is assumed that

$$R_1 = R_2 \text{ and } R_{W1} = R_{W3}$$

the transfer function above reduces to:

$$V_{OUTA3} = V_{RTD}$$

The voltage signal at the output of A_3 is filtered with a 2nd order, low pass filter created with A_4 , R_3 , C_3 , R_4 , and C_4 . This same signal is also gained by the resistors R_5 and R_6 .

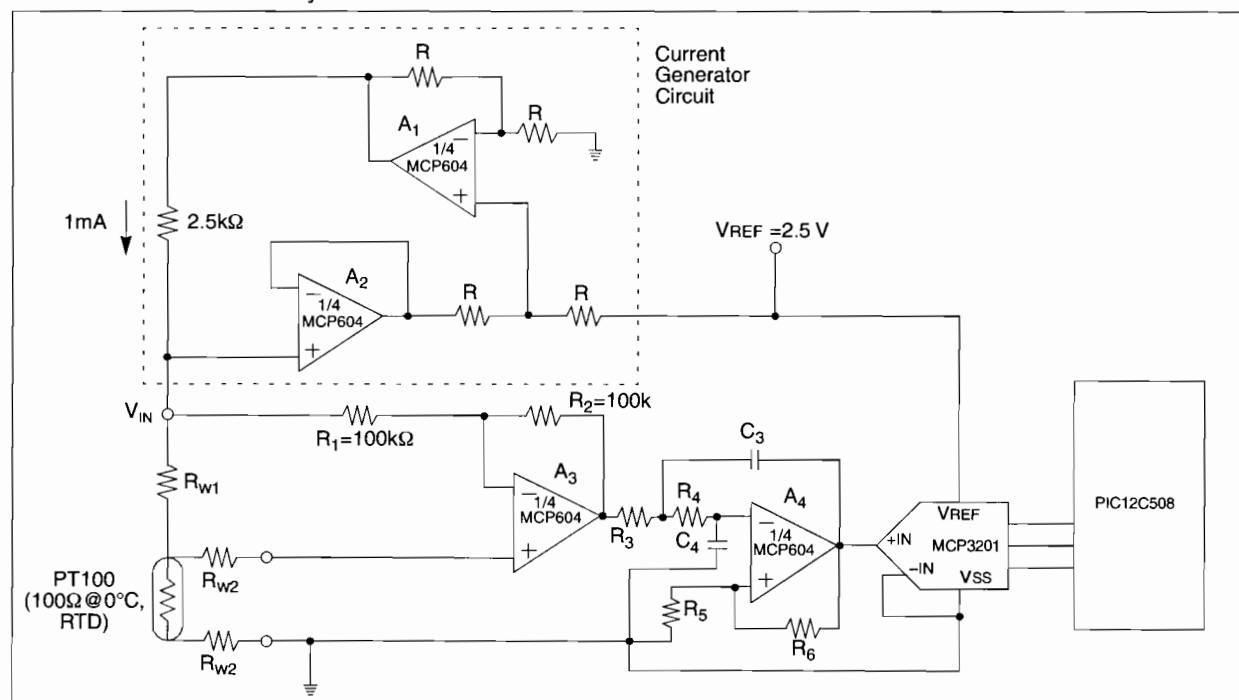


FIGURE 5: This circuit uses an RTD temperature sensitive element to measure temperatures from -200 to 600°C . The current generator circuit from Figure 4 excites the sensor. An operational amplifier, A_3 is used to zero wire resistance error. A fourth amplifier, A_4 is used to gain the signal and filter possible alias interference. A 12-bit converter, MCP3201, converts the voltage across the RTD to digital code for the 8-pin controller, PIC12C508.

CONCLUSION

Although the RTD requires a more circuitry in the signal conditioning path than the thermistor or the silicon temperature sensor, it ultimately provides a high precision, relatively linear result over a wider temperature range. If further linearization is performed in the processor, the RTD circuit can achieve $\pm 0.01^{\circ}\text{C}$ accuracy.

REFERENCES

Baker, Bonnie, "Temperature Sensing Technologies", *AN679*, Microchip Technology Inc.

"Practical Temperature Measurements", *OMEGA CATALOG*, pg Z-11

Baker, Bonnie, "Single Supply Temperature Sensing with Thermocouples", *AN684*, Microchip Technology Inc.

Baker, Bonnie, "Using Operational Amplifiers for Analog Gain in Embedded System Design", *AN682*, Micro-